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# Hydrogen in the extended Venus exosphere

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[1] The nearly absence of water in the atmosphere of Venus is a major difference to the situation at Earth. The actual content of hydrogen in the exosphere is still an open issue, since no in situ measurements are available yet. A different method uses the presence of proton cyclotron waves as an early tracer of ionized planetary hydrogen picked-up by the solar wind, especially in the region upstream of the bow shock. Here, we report long-term observations over two full Venus-years of upstream proton cyclotron waves by the magnetometer on the Venus Express spacecraft, which indicate permanent ionization and pick-up of hydrogen by the solar wind upstream of the planetary bow shock up to high altitudes. The pick-up protons are shown to be of planetary origin, whereas other sources of neutral hydrogen have only negligible contribution. Therefore, the observation of upstream proton cyclotron waves in the solar wind is a clear indication for the existence of an extended neutral hydrogen corona at Venus, with significant local number densities up to an altitude of eight planetary radii. Recent observations of the exospheric Lyman- $\alpha$  emission also indicate hot neutral hydrogen densities which are higher than expected. **Citation:** Delva, M., M. Volwerk, C. Mazelle, J. Y. Chaufray, J. L. Bertaux, T. L. Zhang, and Z. Vörös (2009), Hydrogen in the extended Venus exosphere, *Geophys. Res. Lett.*, **36**, L01203, doi:10.1029/2008GL036164.

## 1. Introduction

[2] Observations from spacecraft and planetary orbiters revealed a large variety in the present atmospheric and exospheric conditions of the planets in the Solar System. For Venus, Earth and Mars, a common origin and similar composition of the environment at times of their formation is generally accepted. Although Venus and Earth have comparable masses and gravity, the difference in water-content at the two planets cannot be explained only by higher thermal escape of hydrogen at Venus. An important aspect is the absence of a Venus-intrinsic magnetic field, where no magnetosphere protects the outer neutral atmosphere from being accessed and depleted

by the solar wind [Zhang *et al.*, 2008]. Ionization of the neutrals by several processes leads to wave generation at the cyclotron frequency in the plasma frame [Gary, 1991]. The occurrence of waves at the local ion cyclotron frequency in the spacecraft frame in the observed magnetic field at a planet, comet or satellite therefore is a direct proof of pick-up of the specific ion from the planetary environment to the solar wind, e.g. at Mars [Russell *et al.*, 1990; Brain *et al.*, 2002], at Saturn [Leisner *et al.*, 2006], at the Galilean satellites Io and Europa [Huddleston *et al.*, 1997; Volwerk *et al.*, 2001], in the environment of active comets [e.g., Tsurutani and Smith, 1986; Johnstone *et al.*, 1987]. Only recently, proton cyclotron waves (PCWs) upstream of the Venus bow shock were reported from the magnetometer observations on the Venus Express mission [Delva *et al.*, 2008a], giving direct evidence that Venus is losing hydrogen to the solar wind. Here, we discuss the consequences for the Venus neutral exosphere of the first long term observations of PCWs in the region upstream of the planetary bow shock, obtained from the magnetometer MAG aboard Venus Express.

## 2. Ion Cyclotron Wave Frequency at the Spacecraft

[3] The frequency of the ion cyclotron waves as observed in the spacecraft frame is the crucial criterion to identify them as generated by planetary ions and not by species of solar wind origin; furthermore, they are transverse waves, propagating nearly parallel to the magnetic field [Mazelle *et al.*, 2004]. In the solar wind frame, a pick-up ion with gyrofrequency  $\Omega_i$  ( $\Omega_i = q/m B$ ; mass  $m$ , charge  $q$ , magnetic field strength  $B$ ) will be resonant with a solar wind wave of frequency  $\omega$ , through the ion/ion right hand resonant instability with dispersion. Assuming parallel propagation and that the original velocity of a planetary particle at time of ionization is negligible with respect to the solar wind velocity  $V_{SW}$ , the wave will be observed at the spacecraft with frequency [see Delva *et al.*, 2008b, and references therein]

$$\omega_{sc} \approx \pm \Omega_i \quad (1)$$

which is independent from the pitch angle  $\alpha(V_{SW}, \mathbf{B})$ . Therefore, the waves will be observed at the local ion gyrofrequency in the spacecraft frame and with specific left-hand polarization due to the anomalous Doppler-effect [Mazelle and Neubauer, 1993]. This fact immediately excludes confusion with ULF waves generated by solar wind protons back-streaming from the bow shock, which will be observed at the spacecraft at frequencies much lower

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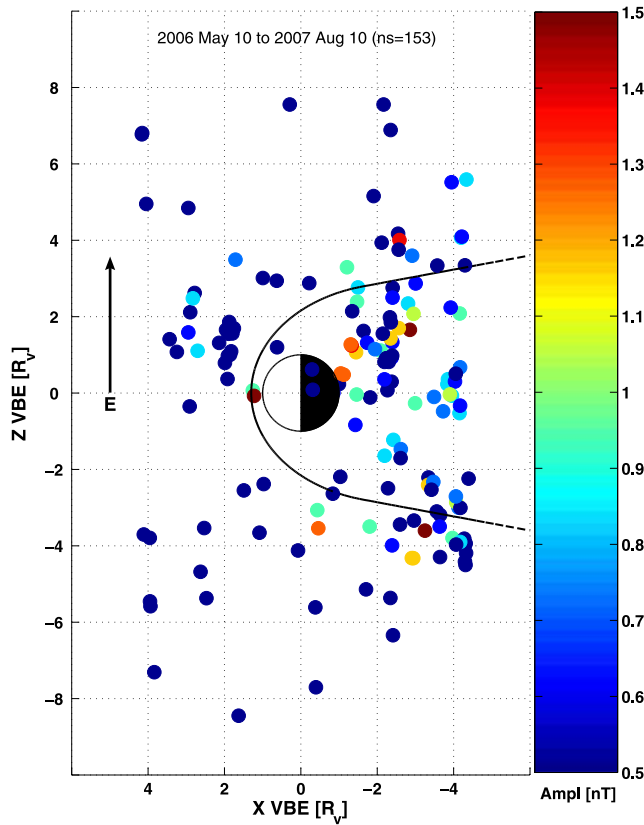
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**Figure 1.** Positions of observations of proton cyclotron waves for two Venus-years in the  $(x, z)_{VBE}$  plane of the electro-magnetic coordinate system VBE; the dashed line denotes the bow shock.

than the cyclotron frequency [Gary, 1991] and occur only within the foreshock.

### 3. Observations by the Venus Express Magnetometer

[4] The Venus Express spacecraft revolves in a polar, elliptical orbit with 24 hr period around Venus [Svedhem *et al.*, 2007] and carries a magnetometer MAG [Zhang *et al.*, 2008]; it is approximately 22 hr per orbit in the solar wind. A survey investigated the MAG data from two Venus-years (10-05-2006 to 10-08-2007) for upstream PCW occurrences in time steps of 10 min, within 4 hr from the bow shock crossings or up to a maximal distance of 9 Venus radii ( $R_V$ ) from the Venus-Sun line [Delva *et al.*, 2008b]. The authors detected PCWs in 1% of the investigated 10 min time-intervals, with (10 min)-mean magnetic field direction mainly at cone angle  $\theta(-V_{SW}, \mathbf{B}) = 38^\circ$  or  $142^\circ$ , there is no correlation with the spacecraft's location in the foreshock region or not; the waves' occurrence in space [Delva *et al.*, 2008b, Figure 7] is similar to Mars [Brain *et al.*, 2002] but up to, for Venus, unexpected high altitudes.

[5] To study the source of the pick-up protons, we here analyze the positions of the PCW occurrences in a Venus centered electro-magnetic coordinate system VBE ( $x_{VBE}$  axis positive towards the Sun (and opposite to  $V_{SW}$ ),  $y_{VBE}$  axis positive in direction of local mean magnetic field component perpendicular to Venus-Sun line,  $z_{VBE}$  axis positive in direction of local motional electric field  $\mathbf{E} = -V_{SW} \times \mathbf{B}$ ),

where the mean magnetic field lines are always parallel to the  $(x, y)_{VBE}$  plane and positive in the  $+y_{VBE}$  direction; Figure 1 shows the positions in the  $(x, z)_{VBE}$  plane. PCWs are observed up to  $\sim 9 R_V$  from the Venus-Sun line, as well as up to  $\sim 4 R_V$  towards the Sun from the terminator plane, which is the limit of the Venus Express orbit in this direction. PCWs occur up to large distances from the planet, a comparable number is found in regions with positive (56%) and negative (44%) value of the  $z_{VBE}$  component; i.e. there is no apparent difference in the spatial distribution in positive and negative regions of the electric field.

[6] The above result is unexpected: first, PCWs occur up to  $\sim 8 R_V$  altitude, indicating that there is hydrogen pick-up to at least these distances; second, PCWs occur far into the negative motional electric field region, although there is no known mechanism to move ions across the magnetic field lines and against the electric field into this region.

[7] However, PCWs are evidence for ongoing pick-up of hydrogen at the observation point or at a location on or near the magnetic field line through the observation point (i.e. on lines with constant  $z_{VBE}$  in Figure 1) since the waves propagate at small angle to the mean magnetic field. If the waves were generated non-locally, i.e. in regions of high neutral hydrogen density closer to the planet, and subsequently propagated in the solar wind plasma to larger distances, damping would take place and significant signals could not be expected at the positions where they were observed. Moreover, for observations in direction towards the Sun and far from the planet ( $x_{VBE} > 3 R_V$ ), the waves should have propagated against the solar wind flow with a velocity larger than the solar wind speed, which is a very unlikely condition.

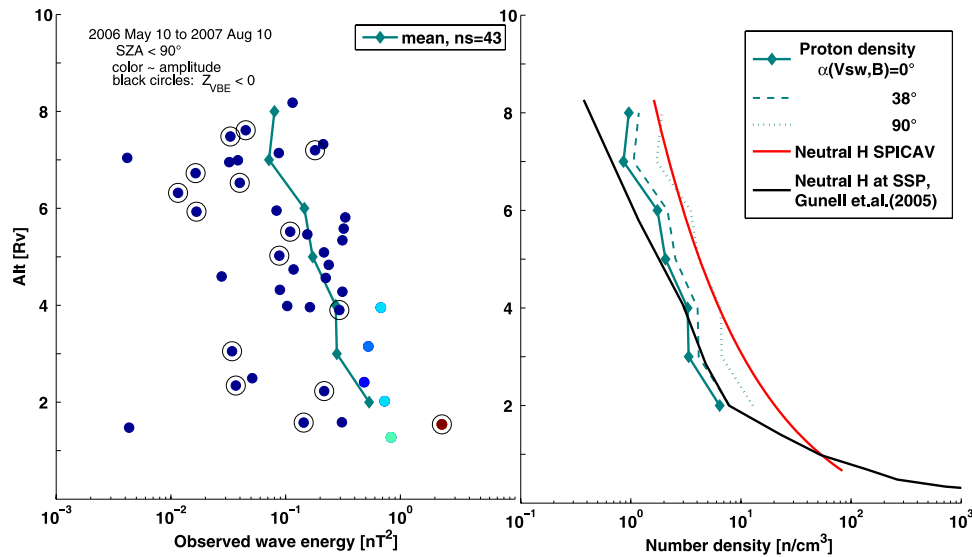
[8] The only explanation for PCW generation in regions of large negative  $z_{VBE}$  or large positive  $x_{VBE}$  is that there is sufficient local neutral hydrogen to be picked up at initial ionization, far from the planet and independent from the motional electric field. Further supply of freshly picked-up ions under the prevailing nearly (anti-) parallel conditions of the solar wind velocity and the magnetic field enables significant wave growth [Brinca, 1991; Gary, 1991], leading to observable left-handed polarized waves in the spacecraft frame.

### 4. Consequences for the Extended Hydrogen Exosphere

[9] Assuming that the waves at saturation stage are generated locally, we calculate the required proton density in the generation area. Based on quasi-linear theory, which describes the transition from a ring-beam to an isotropic shell first by pitch-angle scattering and then to a thick shell by energy diffusion, the total free energy for wave generation in a pick-up ion ring distribution is, in first approximation for small ratios  $V_A/V_{SW}$  (which is shown to be fulfilled below) given by the equation

$$E_{free} = \frac{1}{4} m_i n_i V_A V_{SW} \left[ (1 + \cos \alpha)^2 + (1 - \cos \alpha)^2 \right] \quad (2)$$

where  $m_i$  is the mass of the ion,  $n_i$  the number density,  $V_A$  the Alfvén velocity,  $V_{SW}$  the solar wind velocity, and the pitch angle  $\alpha(V_{SW}, \mathbf{B})$  [Huddleston and Johnstone, 1992]. Equating the observed PCW energy to a fraction of the free



**Figure 2.** Observed wave energy on Venus dayside as function of altitude and required proton density. (left) Wave energy for newly generated PCWs for  $\text{SZA} < 90^\circ$ ; color coding as in Figure 1, black circles for negative  $z_{VBE}$ . (right) Required proton density to generate the observed waves for  $\text{SZA} < 90^\circ$ , maximum energy transfer efficiency ( $\phi = 1$ ) and different pitch angles  $\alpha$ . The black line denotes the neutral hydrogen density from atmospheric models [Gunell et al., 2005]; the red line is the neutral hydrogen density determined from SPICAV Lyman- $\alpha$  observations.

energy in the ring-distribution  $E_{PCW} = \phi E_{free}$  leads to the required ion density  $n_i$  where  $\phi$  describes the efficiency of ring energy transfer to the waves ( $\phi \leq 1$ ). Recent simulation studies indicate that a low value for the efficiency factor  $\phi = 0.25\text{--}0.30$  is realistic [Cowee et al., 2007].

[10] The observed wave energy from newly generated waves is calculated using only waves observed for solar zenith angle  $\text{SZA} < 90^\circ$ , considered to be freshly generated from local ion pick-up, omitting waves possibly already grown to larger amplitude during propagation (Figure 2, left). To obtain a lower limit for the minimum ion density, we use a maximal efficiency factor  $\phi = 1$ . For nominal solar wind conditions at Venus,  $V_{SW} = 400 \text{ km s}^{-1}$ ,  $V_A = 55 \text{ km s}^{-1}$  ( $V_A/V_{SW} \approx 0.1375$ , for  $B = 8 \text{ nT}$  and solar wind proton number density  $n_{pSW} = 10 \text{ cm}^{-3}$ ), we obtain the required ion number density as function of the altitude (Figure 2, right), as a lower limit for pitch angle  $\alpha = 0^\circ$ ; the density for  $\alpha = 38^\circ$  is for the prevailing pitch angle from the data-set [Delva et al., 2008b].

[11] The PCWs are not observed at all times in the magnetometer data, which means that the derived neutral densities are not permanently available. However, mechanisms must exist to provide sufficient local neutrals for long enough times, such that waves with the observed energy are generated.

## 5. Discussion

[12] To present, no in-situ observations of planetary ion densities are available at high altitudes in the solar wind, neither from the Pioneer Venus Orbiter (PVO) [Phillips and McComas, 1991] nor from ASPERA on Venus Express [Barabash et al., 2007]. Optical observations of the Lyman- $\alpha$  airglow from Mariner, Venera [Rodríguez et al., 1984] and PVO spacecraft [Nagy et al., 1990] proved the existence of an “extended hydrogen corona” at Venus, merely confined to altitudes of  $\sim 4 R_V$ . No observed densities are available

for higher altitudes; moreover, existing models have already low densities at much lower altitudes [Hodges, 1999], so we compare with model neutral hydrogen densities obtained in a recent study, where hot and thermal populations of atomic hydrogen are included [Gunell et al., 2005]. The model neutral hydrogen density, shown in Figure 2 (right) for the subsolar point, is of the same order of magnitude as the ion density obtained from the PCW observations. Taking the ionization frequency of  $1.4 \cdot 10^{-7}$  [Kallio et al., 2006] into account, the calculated ion densities appear to be overestimated by equation (2); however, theoretical calculations as well as numerical simulations show that the wave amplitude at saturation stage is linearly related with the density of the particles [e.g., Lemons et al., 1979]. Thus, the PCW observations give a very clear indication that the real local neutral hydrogen density is substantially higher than expected.

[13] We now consider if sources other than initial ionization of neutral planetary hydrogen can be significant. For Mars, secondary pick-up from fast planetary hydrogen has been proposed [Wei and Russell, 2006]; energetic neutral atoms (ENAs) are generated through neutralization of pick-up planetary protons while in gyrational drift around the magnetic field lines. Conserving their momentum at neutralization, the ENAs can propagate in any direction; if secondary ionization takes place, PCWs could be generated again, mainly downstream from the initial ionization position and to the side of the planet. However, neutralization frequency and ionization frequency are both low [Kallio et al., 1997, 2006] such that a significant ion density at distant positions is not expected from this mechanism. As another possible source, existing theoretical and simulation studies at Mars discuss the occurrence of ENAs from precipitating solar wind protons, which were neutralized upstream of the bow shock, or downstream whilst already being shocked and slowed down in the magnetosheath [Kallio and Barabash, 2001; Holmström et al., 2002]. In



these studies, it is assumed that the momentum of the solar wind proton is conserved in the neutralization process, which is only valid for ENAs with energies above 50 eV. Therefore, ENAs produced upstream of the Mars bow shock keep their large velocity in the neutralization process and their outflow is mainly to the night side with maximum at  $\text{SZA} = 150^\circ$ . ENAs produced from shocked solar wind have small velocities, their influx on the dayside of Mars is low and outflow is also mainly to larger SZA, with a maximum at  $115^\circ$  [Holmström *et al.*, 2002].

[14] Transferring this approach to Venus enables an estimation, if neutral hydrogen from precipitating solar wind protons can be a considerable source for pick-up and PCW generation. ENAs from unshocked protons will still have large velocity components parallel to the mean magnetic field. Therefore, generated waves from pick-up of these particles will be observed at the spacecraft at frequencies largely different from the local proton frequency. ENAs from shocked solar wind protons could contribute and their main flux is expected for  $\text{SZA} > 90^\circ$ ; however, from our data analysis we need more hydrogen density for  $\text{SZA} < 90^\circ$  to explain the observed PCWs. Even if we consider the so-called ENA albedo, the additional flux of ENAs to the solar side of the planet ( $\text{SZA} < 60^\circ$ ) [Holmström *et al.*, 2002] is still negligible with respect to the ion density required for the observed PCWs. Furthermore in the case of Venus, analysis of ENAs generated from the solar wind protons leads to a resulting total ENA outflow lower than at Mars because the ENAs are produced at a much lower altitude above the planet [Gunell *et al.*, 2005]; therefore, the above described ENA mechanism will be even weaker at Venus.

[15] Recently, jets of ENAs with energies in the range 0.3–3 keV were reported at Mars which are likely to be emitted conically from the subsolar region and of solar wind proton origin [Futaana *et al.*, 2006]. If such jets exist also at Venus, the energy of these neutrals is too high and eventual pick-up and wave generation will be observed at the spacecraft at a frequency different from the local proton cyclotron frequency.

[16] The above considerations on local hydrogen generated from solar wind protons lead to the conclusion that ENAs from solar wind protons cannot contribute significantly to the pick-up and generation of waves at the local proton cyclotron frequency in the upstream region as observed by MAG.

[17] Interstellar hydrogen from both the local interstellar medium and the “inner source” can also contribute to local pick-up, with a total neutral density  $\leq 3 \times 10^{-4} \text{ cm}^{-3}$  at 0.7 AU [Möbius *et al.*, 2006; P. Wurz, personnel communication, 2008]. This neutral density at the Venus orbit is very low, such that pick-up protons from interstellar hydrogen form only a negligible fraction of the local proton density; also, analysis of the PCW occurrences as function of the ecliptic longitude did not show any enhancement at the main source direction for the interstellar neutrals. In general, interstellar neutrals have such a low density, that the ion beam at their pick-up is not dense enough to produce wave generation [Tsurutani *et al.*, 1994].

[18] Currently, the SPICAV instrument [Bertaux *et al.*, 2007] aboard Venus Express observes the exospheric

Lyman- $\alpha$  emission. The hot hydrogen density profile is derived from forward comparisons between theoretical models and observations above 4000 km altitude. The first results, although sensitive to the Lyman- $\alpha$  interplanetary background, indicate high densities at high altitudes. An example of hydrogen profile fitting well the observations is shown in Figure 2 (right). The uncertainty on the hot hydrogen density at 10,000 km is estimated near  $10 \text{ cm}^{-3}$ . The shape of the neutral density profile determined from the SPICAV observations is in accordance with the shape of the ion density profile from the PCWs.

## 6. Summary and Conclusions

[19] We investigated long-term observations of upstream proton cyclotron waves by the magnetometer on the Venus Express spacecraft over two Venus-years, which demonstrate permanent ionization and pick-up of local neutral hydrogen by the solar wind up to altitudes of  $\sim 8 R_V$ . A density profile for the pick-up protons was obtained from the observed wave energy. Despite consideration of energetic neutral hydrogen from precipitating solar wind protons and from interstellar hydrogen as possible additional source for local pick-up, no significant neutral hydrogen density with the required low velocity in the regions of PCW observations could be identified. It is concluded that the observation of the waves at the local proton cyclotron frequency in the Venus upstream region can only be explained by pick-up of neutral hydrogen from an extended reservoir of planetary origin. Lyman- $\alpha$  observations from the SPICAV instrument aboard Venus Express also indicate a higher neutral hydrogen density than expected.

[20] Until now, there was no indication that the neutral hydrogen corona of Venus reaches out far from the planet. From the presented study, the existence of an extended Venus hydrogen exosphere with local neutral hydrogen densities significantly higher than  $n_H = 2 \text{ cm}^{-3}$  at altitudes of  $5 R_V$  (higher than  $n_H = 1 \text{ cm}^{-3}$  at  $8 R_V$ ) is postulated, to enable generation of proton cyclotron waves with the observed energy for time-intervals from several minutes up to two hours. The nature of this extended exosphere with frequent high local densities is still an open issue and under investigation.

[21] It is noticed that a comparable situation was reported at Mars. Severe solar wind deceleration was observed by the Phobos-2 spacecraft upstream of the Mars bow shock due to pick-up of hydrogen and oxygen; this can only be explained by a more extended and denser hydrogen and oxygen corona [Kotova *et al.*, 1997]. Observations of exospheric Lyman- $\alpha$  emission from the Mars Express spacecraft indicate a similar discrepancy: the neutral hydrogen density required to explain the observations is higher than the predicted values from any model [Chaufray *et al.*, 2008].

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